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Smart Guardian Cane: An ESP32 Based Assistive Device for Visually Impaired and Elderly People

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Abstract: *Visual impairment remains one of the most significant barriers to independent mobility worldwide. According to the World Health Organization, over 2.2 billion people globally suffer from some form of vision loss, and a large fraction of them rely on traditional white canes that offer little beyond basic tactile feedback. These conventional tools fail to detect obstacles at mid-body height, identify water patches on the ground, or provide any form of automated alert — leaving users exposed to preventable accidents on a daily basis.*

This paper presents the Smart Guardian Cane, a low-cost IoT-enabled assistive device built around the ESP32 microcontroller. The system integrates an HC-SR04 ultrasonic sensor for real-time obstacle detection and a water sensor module to identify puddles or wet surfaces. Upon detecting a hazard, the cane triggers an immediate alert through a buzzer and a vibration motor, giving the user rapid sensory feedback. The entire device runs on a compact rechargeable battery, making it lightweight and practical for everyday carry.

Prototype testing demonstrated reliable obstacle detection up to 200 cm and consistent water detection across different surface materials. The system is designed to be affordable, repairable, and expandable — with future enhancements planned to include GPS tracking, a mobile companion app, and AI-powered scene understanding. The Smart Guardian Cane represents a meaningful step toward safer, more autonomous navigation for visually impaired and elderly individuals..

Keywords: Smart Guardian Cane, ESP32, Assistive Technology, IoT, Ultrasonic Sensor, Water Sensor, Visually Impaired, Obstacle Detection

I. INTRODUCTION

Independent mobility is something most people take for granted, but for the estimated 43 million people who are blind and the additional 295 million living with moderate-to-severe visual impairment, navigating everyday environments can be a genuinely hazardous task [1]. A busy footpath, a wet floor, an overhanging branch — obstacles that a sighted person avoids instinctively can cause serious falls, injuries, or worse for someone who cannot see them coming.

The traditional white cane has served as the primary mobility tool for the blind community for over a century. It is simple, light, and universally understood — but it has real limitations. A standard cane sweeps the floor immediately ahead and offers almost no feedback about obstacles at waist or chest height, and none whatsoever about the nature of the surface underfoot. A user walking confidently in dry conditions might step straight into a water puddle with no warning, or walk into an open car door that is well above the cane's detection range.

In recent years, the convergence of affordable microcontrollers, miniaturized sensors, and wireless connectivity has opened a new frontier in assistive technology. Smart cane systems have begun to appear in academic and commercial settings, ranging from simple buzzer-based prototypes to sophisticated devices incorporating GPS, cameras, and machine learning. However, many of these solutions remain out of reach for ordinary users — either prohibitively

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expensive, too bulky to carry comfortably, or dependent on infrastructure like smartphones and internet connectivity that not all users have access to.

The motivation behind this project was straightforward: could we build a genuinely useful, genuinely affordable smart cane that a student engineering team could prototype and validate within a semester? The answer, as this paper demonstrates, is yes. The Smart Guardian Cane uses an ESP32 microcontroller — a well-documented, widely available, and inexpensive platform — paired with an ultrasonic sensor and a water detection module. The result is a cane that detects obstacles ahead and warns the user of wet surfaces, all without requiring any external connectivity or ongoing subscription costs.

This paper is organized as follows: Section II reviews related work in the smart cane domain. Section III formally states the problem. Sections IV through VIII detail the proposed system, its architecture, components, working principle, and implementation. Sections IX through XII present results, advantages, applications, and future scope. Section XIII concludes the paper.

II. LITERATURE REVIEW

The concept of an electronically enhanced walking cane is not new. Researchers have explored it from multiple angles over the past two decades, and a brief survey of existing work helps clarify both the progress made and the gaps that remain.

Bhatlawande et al. [2] proposed a comprehensive navigation system for the visually impaired that combined ultrasonic sensors with a GPS module and a mobile application. Their system demonstrated reliable indoor and outdoor performance but required a smartphone and a stable data connection — constraints that are not realistic for many users in semi-urban or rural India.

Kumar and Ramakrishnan [3] developed a smart cane using an Arduino Uno with two ultrasonic sensors and a vibration motor. While the system worked reasonably well in controlled testing, the Arduino's limited processing power and the absence of wireless capability restricted its scalability. The authors themselves noted that upgrading to a more capable microcontroller would be a logical next step.

Islam et al. [4] incorporated a Raspberry Pi into their assistive cane design, enabling computer vision-based object recognition. The system was impressive in terms of intelligence but required continuous power that a portable battery could not sustain for more than a few hours. Cost was also a significant concern, with the bill of materials exceeding a level that would be practical for mass deployment.

On the IoT side, Elmannai and Elleithy [5] published a comprehensive review of sensor-based assistive technologies and highlighted the growing role of microcontrollers like ESP8266 and ESP32 in enabling low-cost, connected devices. They noted that most existing prototypes lacked real-world validation beyond laboratory settings.

Closer to the present work, Saaid et al. [6] demonstrated a water detection system for the visually impaired using a simple conductive sensor and a buzzer. However, their device was standalone and was not integrated with any obstacle detection capability, meaning users still needed to carry and manage multiple tools simultaneously.

What emerges from this survey is a consistent pattern: existing smart cane designs tend to excel in one area — sensing range, processing power, or connectivity — while sacrificing others. A truly practical solution for a typical visually impaired individual needs to be lightweight, affordable, battery-powered, and capable of handling the two most common immediate hazards: obstacles in the path and wet ground. That is precisely the gap that the Smart Guardian Cane is designed to fill.

III. PROBLEM STATEMENT

The core challenge facing visually impaired individuals is not simply the absence of sight — it is the absence of reliable, real-time information about their immediate environment. While guide dogs and human assistance can provide this information, they are not always available, and the goal of most modern assistive technology is to expand the user's capacity for independent navigation.

Traditional canes address the problem of floor-level obstacles directly in front of the user. But this leaves several critical hazard categories unaddressed:

- Mid-height and overhead obstacles: Objects between knee and head height — furniture, bollards, low-hanging branches, open car doors — are entirely outside the sweep of a standard cane and account for a significant portion of injuries among blind pedestrians.
- Water and wet surface detection: Puddles, flooded pavement sections, and wet tiles present a serious fall risk. No part of a standard cane is designed to identify water or assess surface friction.
- Cognitive and sensory load: Users of traditional canes must maintain constant conscious attention to the cane's tactile feedback. A system that can automate routine hazard detection frees the user's cognitive resources for higher-level navigation decisions.
- Affordability and accessibility: Many smart assistive devices exist only as expensive commercial products or academic prototypes, placing them beyond the reach of the users who need them most — particularly in low- and middle-income countries.

The Smart Guardian Cane addresses all four of these issues within the constraints of a student-built prototype, demonstrating that effective assistive technology does not need to be expensive or complicated.

IV. PROPOSED SYSTEM

The Smart Guardian Cane is an IoT-integrated walking cane that augments the traditional mobility aid with two primary sensing capabilities: forward obstacle detection and underfoot water detection. The core processing unit is the ESP32 microcontroller, which was chosen for its combination of processing power, integrated Wi-Fi and Bluetooth (reserved for future use), dual-core architecture, and remarkably low cost.

The system operates in a continuous sensing loop. The ultrasonic sensor measures the distance to objects in the user's forward path at a frequency of approximately 10 readings per second. If an object is detected within a configurable threshold distance — set to 100 cm in our prototype — the ESP32 immediately activates the buzzer and vibration motor in a pattern that conveys urgency. Simultaneously, the water sensor continuously monitors the conductivity of the ground surface just below the cane tip. Any detected moisture triggers a distinct secondary alert pattern, allowing the user to distinguish between the two types of hazard.

The decision to use a dedicated vibration motor alongside the buzzer was deliberate. In noisy urban environments — busy streets, crowded markets, transit stations — an audio alert alone may not be perceptible. Haptic feedback through vibration is immune to ambient noise and also ensures the device remains useful in situations where the user prefers not to draw attention.

V. SYSTEM ARCHITECTURE

The overall architecture of the Smart Guardian Cane follows a straightforward sense-process-alert pipeline, as illustrated in Fig. 1.

VI. HARDWARE COMPONENTS

A. ESP32 Microcontroller

The ESP32 (Espressif Systems) serves as the brain of the entire system. Operating at 240 MHz across two cores, it comfortably handles real-time sensor polling, distance calculation, and alert management simultaneously. It operates at 3.3V logic, supports both Arduino-compatible C++ and MicroPython programming, and is available for under ₹300 in India — making it an ideal choice for cost-constrained projects. The integrated Wi-Fi and Bluetooth modules are not used in the current prototype but represent an obvious pathway to future enhancements like remote monitoring or emergency alerts.

B. HC-SR04 Ultrasonic Sensor

The HC-SR04 is a well-established ultrasonic ranging module operating at 40 kHz. It emits an ultrasonic pulse and measures the time taken for the echo to return, allowing distance calculation using the simple formula: Distance = (Time × Speed of Sound) / 2. Its effective range spans from 2 cm to 400 cm, with a typical accuracy of ±3 mm in stable conditions. It operates at 5V and draws approximately 15 mA — modest enough to run comfortably from a USB power bank or Li-ion cell. In our prototype, the sensor was mounted at an angle of approximately 15° from horizontal to maximize the detection coverage area for obstacles at waist height.

C. Water / Moisture Sensor

The water detection module used in this prototype consists of a pair of exposed copper traces on a PCB, connected to a comparator circuit that outputs a digital HIGH signal when conductivity between the traces exceeds a threshold — indicating the presence of water or significant moisture. The module includes a built-in potentiometer for sensitivity adjustment, which proved useful during calibration for different surface types. It was mounted just above the cane tip so that it makes contact with the ground surface during the natural sweeping motion of the cane.

D. Buzzer and Vibration Motor

A piezoelectric buzzer provides the primary audio alert. Different patterns — short beeps for obstacles, a continuous tone for water — allow the user to distinguish between hazard types without visual feedback. A 3V coin vibration motor provides the haptic channel. Both components draw minimal current and can be driven directly from an ESP32 GPIO pin through a small NPN transistor, simplifying the circuit.

E. Battery Module

The prototype uses an 18650 lithium-ion cell (2600 mAh) paired with a TP4056 charging module for safe charging via micro-USB. At full load (ESP32 active, both sensors running, alert systems idle), the system draws approximately 180 mA, giving an estimated runtime of around 12 hours on a single charge — comfortably sufficient for a full day of use. The battery and charging module are housed in a compact case that attaches to the upper shaft of the cane.

VII. WORKING PRINCIPLE

The Smart Guardian Cane operates through a continuous sensing and response loop. The following steps describe one complete cycle of operation:

Step 1 — System Initialization: On power-up, the ESP32 initializes all GPIO pins, configures the ultrasonic trigger and echo pins, and sets the water sensor input pin with a pull-down resistor. A brief double-beep confirms successful initialization.

Step 2 — Ultrasonic Pulse Emission: The ESP32 sends a 10 µs HIGH pulse to the HC-SR04 trigger pin. This causes the sensor to emit eight 40 kHz ultrasonic pulses.

Step 3 — Echo Detection and Distance Calculation: The echo pin goes HIGH when the reflected pulse returns. The ESP32 measures the duration of this HIGH pulse and calculates distance using: Distance (cm) = (Echo Duration in µs) / 58.2.

Step 4 — Obstacle Threshold Check: If the calculated distance is less than or equal to 100 cm, the system flags an obstacle condition. The buzzer emits a rapid intermittent beep pattern and the vibration motor activates for 300 ms.

Step 5 — Water Sensor Read: Simultaneously, the ESP32 reads the digital output of the water sensor module. A HIGH signal indicates moisture above the threshold. This triggers a distinct continuous buzzer tone and a longer vibration pulse (600 ms) to differentiate it from the obstacle alert.

Step 6 — Combined Hazard Handling: If both an obstacle and water are detected simultaneously, the system prioritizes the obstacle alert while simultaneously activating the water indicator vibration pattern, ensuring neither hazard goes unnoticed.

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Step 7 — Loop Repetition: After a 100 ms delay, the cycle repeats from Step 2. This gives the system a sensing frequency of approximately 10 Hz — fast enough to detect a walking-speed encounter with an obstacle before impact.

VIII. IMPLEMENTATION

A. Hardware Assembly

The hardware assembly involved mounting the HC-SR04 sensor at the upper shaft of the cane at an angle to maximize mid-body obstacle detection. The water sensor was secured just above the rubber tip using a custom 3D-printed bracket. The ESP32 development board, buzzer, and vibration motor were housed inside a small ABS enclosure attached to the cane's handle. Wiring used flexible 22 AWG silicone wire to survive the repeated flexing of normal use. All connections were solderered and heat-shrink insulated for durability.

B. Programming Logic

The firmware was written in Arduino-compatible C++ using the ESP-IDF toolchain via the Arduino IDE. The main loop follows the sense-process-alert structure described in Section VII. Distance thresholds and alert patterns are defined as constants at the top of the code, making reconfiguration straightforward. The code also includes a simple debouncing mechanism for the water sensor to prevent false alerts from brief surface vibrations.

Fig. 2. Core firmware loop (simplified pseudocode)

C. Testing Methodology

Testing was conducted in three phases. In the first phase, the ultrasonic sensor was tested independently in a controlled corridor environment, measuring detection accuracy against objects of different materials — a wooden board, a metal pole, and a fabric curtain — at distances ranging from 20 cm to 300 cm. In the second phase, the water sensor was tested against still water, running water, and damp cloth surfaces. The third phase simulated real walking conditions, with a test subject wearing a blindfold and navigating a prepared course containing both obstacle and water hazards.

IX. RESULTS AND DISCUSSION

A. Obstacle Detection Performance

Table I summarizes the obstacle detection results across three material types and five distance intervals.

The results indicate excellent detection reliability for hard surfaces (wood, metal) at all tested distances. Soft or porous materials like fabric showed slightly reduced accuracy at greater distances, primarily because they absorb some of the ultrasonic energy rather than reflecting it cleanly. In practice, most real-world obstacles (walls, furniture, vehicles, people) present hard reflective surfaces, so the real-world accuracy is expected to closely match the wood/metal figures.

B. Water Detection Performance

Water detection was tested across five surface conditions: standing water on concrete, standing water on tile, damp concrete, damp cloth, and dry surfaces (false-positive testing). The sensor correctly identified all water/damp conditions in 97 out of 100 trials and produced zero false positives on dry surfaces. The three missed detections occurred with very thin water films on smooth tile, where the conductivity was marginally below the detection threshold. Adjusting the sensitivity potentiometer slightly resolved this issue.

C. Real-World Navigation Trial

In the blindfolded navigation trial, participants successfully avoided all marked obstacles and received correct water alerts in 94% of test runs. Participants reported that the distinct alert patterns for obstacles versus water were easy to learn and interpret after only a short familiarization period. Average reaction time from alert to user response was measured at 0.8 seconds — comfortably within the safety margin for a walking-speed encounter.

Overall, these results confirm that the Smart Guardian Cane performs reliably within its design specifications and provides meaningful safety improvements over a standard cane in both controlled and simulated real-world settings.

X. ADVANTAGES

- Low Cost: The complete bill of materials is under ₹1,200 (approximately USD 15), making the device accessible to users across a wide range of economic circumstances. This is an order of magnitude cheaper than most commercial smart cane products.
- Portability: The electronics add less than 150 grams to the cane's total weight. The compact form factor does not impede normal cane use and is unobtrusive in public settings.
- No External Dependencies: The system requires no internet connection, no smartphone, and no subscription service. It operates entirely standalone, which is critical for users in areas with limited connectivity.
- Dual Sensory Feedback: The combination of audio and haptic alerts ensures the system remains effective in noisy environments where audio alone might be insufficient.
- Expandability: The ESP32's remaining GPIO pins, Wi-Fi radio, and Bluetooth capability provide a natural upgrade path for future features. Adding GPS, a panic button, or a companion app requires only firmware changes and minimal additional hardware.
- Reliability: With no moving parts except the vibration motor, and no complex software dependencies, the system is highly reliable in everyday use.

XI. APPLICATIONS

A. Visually Impaired Users

The primary application is straightforward: any blind or severely visually impaired individual who uses a cane for navigation can benefit from the enhanced hazard detection. The device is particularly valuable in unfamiliar indoor environments (hotel lobbies, offices, hospitals) where obstacle layouts change frequently.

B. Elderly Users

Many elderly individuals have reduced vision and slower reflexes, making falls a serious concern. The Smart Guardian Cane's water detection capability directly addresses one of the most common causes of falls among the elderly — wet floors. The device can function as a general-purpose safety-enhanced walking stick even for users who are not clinically visually impaired.

C. Healthcare and Rehabilitation Settings

Hospitals, rehabilitation centers, and care homes could equip patients recovering from vision-affecting conditions — stroke, cataract surgery recovery, diabetic retinopathy — with Smart Guardian Canes during the rehabilitation period as a safety aid.

XII. FUTURE SCOPE

The current prototype, while functional and validated, is explicitly a first-generation device. Several enhancements are planned or under consideration for subsequent versions:

- GPS Integration: Adding a GPS module would allow the device to log the user's location and transmit it to a caregiver or emergency contact via the ESP32's built-in Wi-Fi. A geofencing feature could alert the caregiver if the user strays outside a defined safe area.
- SOS Emergency Button: A single large button on the handle, when held for two seconds, could send an automated emergency message with GPS coordinates to pre-configured contacts via a paired smartphone or directly via a GSM module.
- Mobile Companion Application: A Bluetooth Low Energy (BLE) companion app could allow caregivers to adjust detection thresholds remotely, review travel logs, and receive real-time location updates. The ESP32's built-in BLE makes this enhancement hardware-ready without any modifications to the current prototype.
- AI-Powered Scene Understanding: Integrating a small camera module and running a lightweight object detection model (MobileNet or similar) on a secondary processor could allow the device to recognize specific hazards — stairs, crosswalks, signage — and provide voice-guided instructions through a small speaker.

- Voice Feedback: Replacing or supplementing the buzzer with a small speaker and text-to-speech output (e.g., "Obstacle 60 centimeters ahead") would provide richer, more actionable information with no increase in cognitive load.
- Miniaturization: A custom PCB integrating the ESP32, sensor interfaces, and power management into a single board would significantly reduce size and weight, and improve moisture resistance through conformal coating.

Each of these enhancements is technically feasible with available off-the-shelf components and represents a natural next step for a more capable version of the device.

XIII. CONCLUSION

This paper has presented the Smart Guardian Cane, a low-cost, IoT-enabled assistive device that addresses two of the most significant daily hazards facing visually impaired and elderly individuals: mid-path obstacles and water-covered surfaces. By combining an ESP32 microcontroller with an HC-SR04 ultrasonic sensor and a water detection module, we were able to build a working prototype for under ₹1,200 that provides reliable, real-time dual-sensory (audio + haptic) alerts to the user.

Laboratory and simulated real-world testing demonstrated obstacle detection accuracy above 95% for hard-surface obstacles up to 200 cm, and water detection accuracy of 97% across diverse surface conditions. A blindfolded navigation trial confirmed that users could successfully interpret and respond to the device's alert patterns with minimal training.

The Smart Guardian Cane does not attempt to replace the judgment and spatial awareness of the user — it augments them. By automating routine hazard detection, it reduces the cognitive burden of navigation and allows the user to direct their attention toward higher-level decisions about route and direction. In doing so, it takes a meaningful step toward the broader goal of assistive technology: empowering people to live more independently, safely, and with greater dignity.

Future work will focus on GPS integration, emergency alert functionality, and a mobile companion application, with the longer-term aspiration of incorporating AI-based scene understanding to create a truly intelligent navigation assistant.

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